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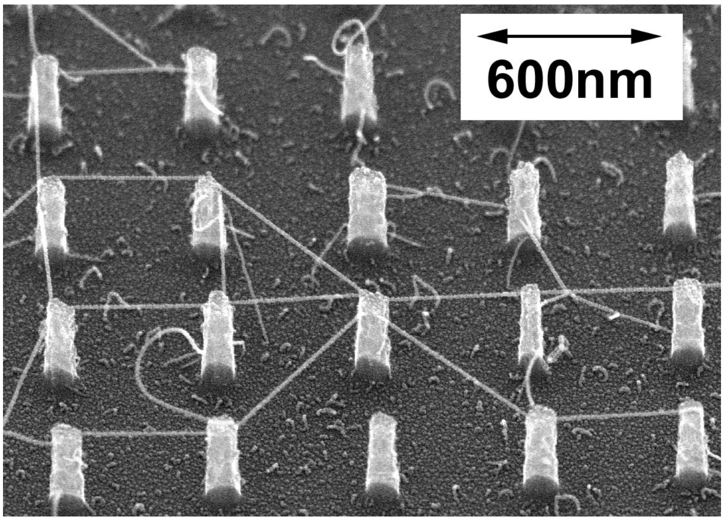
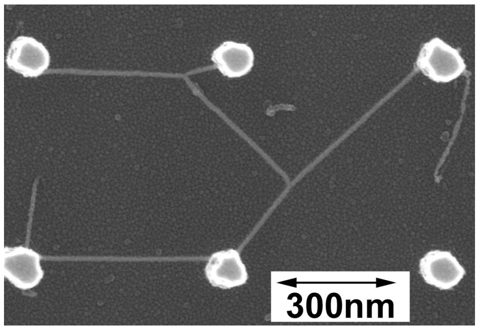
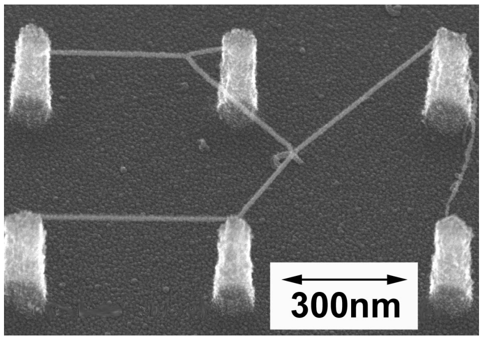


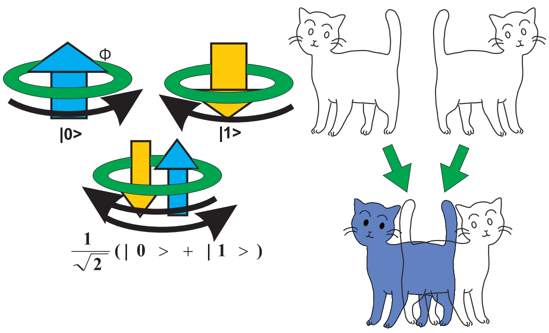




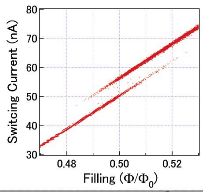
Scanning electron microscopy images of single-walled carbon nanotubes grown between Si pillars fabricated by SOR lithography

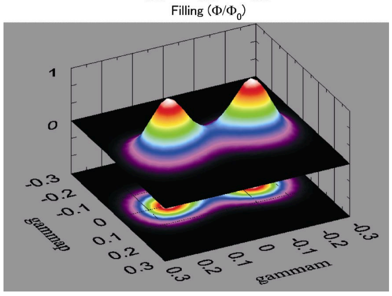
Carbon Nanotube Interconnection

Carbon nanotubes are promising for wiring and connecting nano-scale devices because of their peculiar mechanical and electrical properties. We have proposed a self-assembled carbon nanotube interconnection and succeeded in fabricating a network on an array of nanometer-scale Si pillars. (Page 15)



Qubit states and Schrödinger's cat

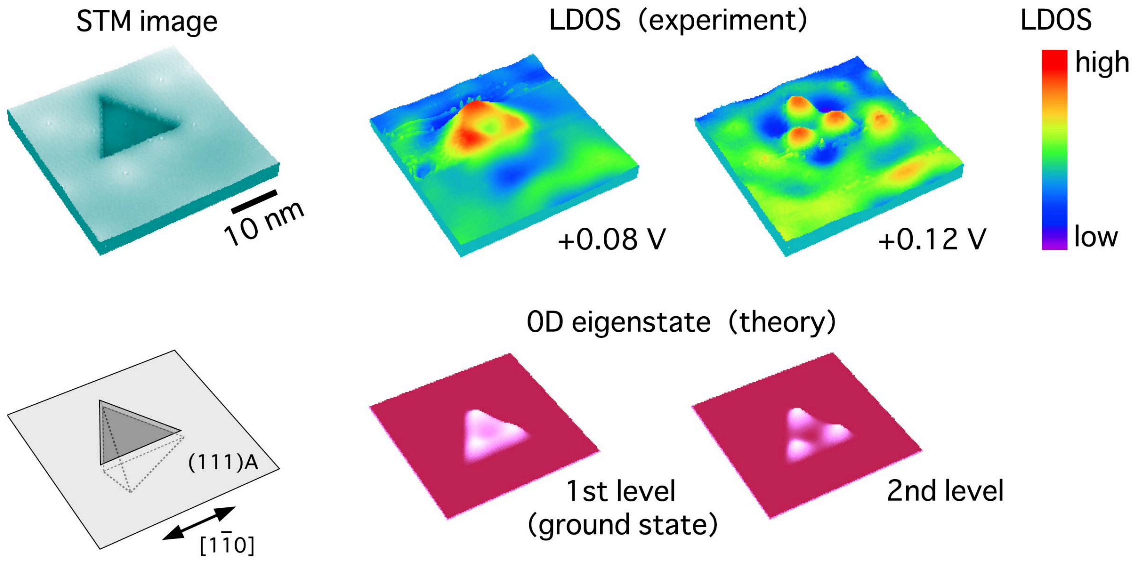




Readout Characteristics and wave functions

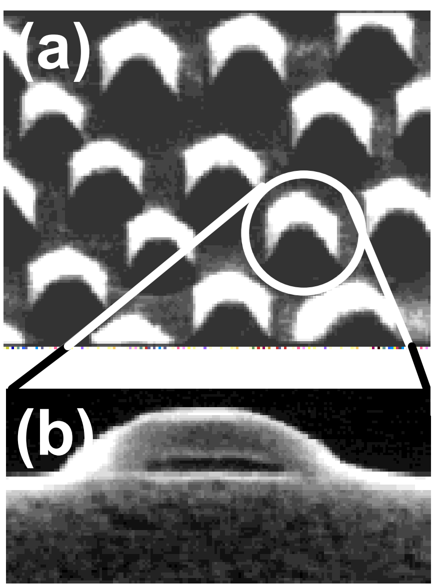
Quantum Computer with Superconductor

Readout characteristics of a quantum bit (qubit), which is a basic element of a quantum computer, are studied. We fabricated flux qubit, which uses superconductor ring, and confirmed readout distingishability between two opposite current states. The superconductor ring is also interesting from the viewpoint of pure quantum physics and is a manifestation of Schrödinger's cat. (Page 20)

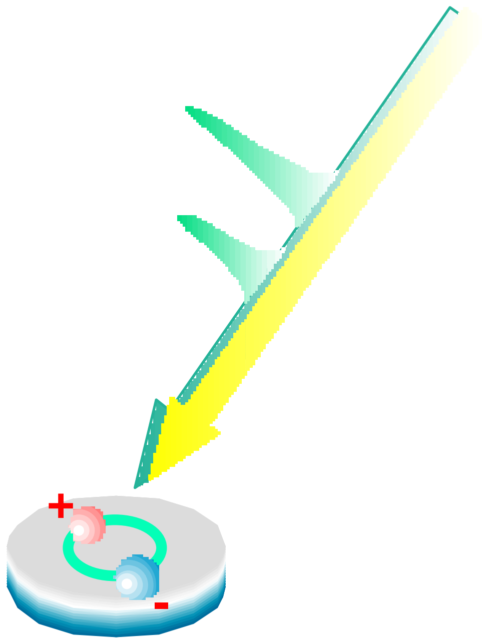


Imaging of Zero-dimensional States in a Semiconductor Nanostructure

Utilization of the quantum mechanical wave phenomena in nanostructures is important for developing quantum devices and quantum computers. We have imaged the local density of states (LDOS) of zero-dimensionally confined electron waves by using scanning tunneling microscopy (STM) at low temperatures. It is found that the LDOS distribution of a semiconductor nanostructure coincides with the probability distribution of electrons in a zero-dimensional structure (a quantum dot). (Page 23)



SEM images of quantum dot



Coherent Optical Control of Quantum Dot Exciton Superposition

Experimental demonstration was made of coherent optical control of single-dot exciton by a phase-locked pulse train (right figure): The first pulse creates an exciton coherent superposition that is alterd by the following pulses with phase control. Left figure (a) top view of the InGaAs quantum dot array, and (b) cross-sectional view of an isolated structure showing disk-shaped InGaAs region buried in Al-rich alloy. (Page 30)

Preface

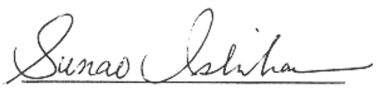
We greatly appreciate your support and interest in the research activities of NTT Basic Research Laboratories.

The objectives of the NTT Basic Research Laboratories are to find new scientific principles and create innovative technologies that will form the infrastructure of an information sharing society characterized by "Informative Ambience". As we move toward our goals, we continue to pioneer research fields by developing innovative technologies and to produce outstanding scientific achievements. Our research interests are device physics, functional material science, quantum electronic physics, and quantum optics, and this work engages the efforts of about one hundred researchers. Nanotechnology designed to control nano-structures at molecular and atomic levels and Quantum Information Technology based on quantum mechanical principles are key words in relation to our research activities.

To maintain our innovative research activities and open the frontiers of science, we believe it is essential to pursue an open research policy and recognize the wide variety of talent that exists around the world. We run various scientific exchange programs with universities and institutes and undertake many joint projects. Moreover, international symposia are regularly held to promote further progress in specific research fields. We hosted the International Symposium on Mesoscopic Superconductivity and Spintronics 2002 in March this year.

This booklet, "Research Activities in NTT Basic Research Laboratories Vol. 12," provides an overview of our research activities in 2001. We hope this booklet will encourage mutual understanding and further collaboration among all scientists.

July 2002



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Contents

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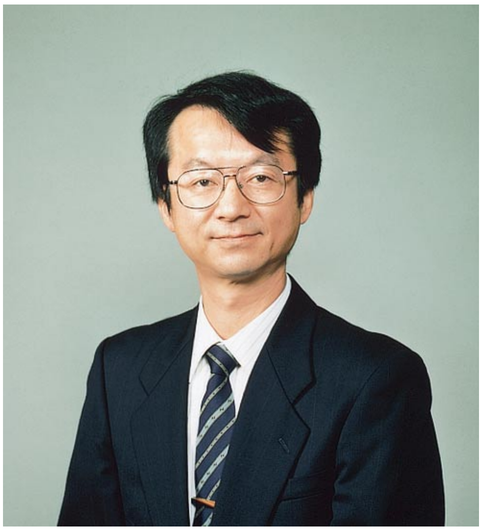

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Dr. Atsushi Yokoo	Dr. Akihiko Shinya	

Distinguished Technical Member

Toshiki Makimoto was born in Tokyo on January 16, 1960. He received the B.E., M.S. and Ph.D. degrees in electrical engineering from the University of Tokyo in 1983, 1985 and 1993, respectively. He joined NTT Basic Research Laboratories in 1985. He was a visiting researcher in University of California, Santa Barbara, USA during 1993-1994. Since 1985, he has engaged in epitaxial growth of III-V compound semiconductors using metalorganic vapor phase epitaxy (MOVPE) and flow-rate modulation epitaxy (FME), in-situ monitoring of epitaxial growth using surface photo-absorption (SPA), characterization of heavily doped semiconductors, heterojunction bipolar transistors (HBTs), and nano-structure selective area growth using scanning tunnel microscopy (STM). His current interests are epitaxial growth of nitride semiconductors and nitride semiconductor devices. He is a member of the Japan Society of Applied Physics and Materials Research Society.

Toshimasa Fujisawa was born in Tokyo on May 23, 1963. He received the B.E., M.S. and Ph.D. degrees in electrical engineering from Tokyo Institute of Technology in 1986, 1988 and 1991, respectively. He joined NTT Basic Research Laboratories in 1991. He was a guest scientist in Delft University of Technology, Delft, the Netherlands during 1997-1998. Since 1991 he has engaged in the study of semiconductor fine structures fabricated by focused-ion-beam technique and electron-beam lithography technique, transport characteristics of semiconductor quantum dot. His current interests are single-electron dynamics in quantum dots, and their application to quantum information technologies. He is a member of the Japan Society of Applied Physics, and the Physical Society of Japan.

Distinguished Technical Member

Masaya Notomi was born in Kumamoto, Japan, on 16 February 1964. He received his B.E., M.E. and Dr. Eng. degrees in applied physics from University of Tokyo, Tokyo, Japan in 1986, 1988, and 1997, respectively. In 1988, he joined Nippon Telegraph and Telephone Corporation, NTT Optoelectronics Laboratories, Atsugi, Japan. Since then, his research interest has been to control the optical properties of materials and devices by using artificial nanostructures, and engaged in research on semiconductor quantum wires/dots and photonic crystal structures. He has been in NTT Basic Research Laboratories since 1999, and is currently working on light-propagation control by use of various types of photonic crystals. From 1996-1997, he was with Linköping University in Sweden as a visiting researcher. He is a member of the Japan Society of Applied Physics, and the American Physical Society.

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Ⅰ. Research Topics

Overview of Device Physics Research

Toshio Ogino
Device Physics Laboratory

In the Device Physics Laboratory, we are studying silicon (Si) nanotechnology as a means of creating the ultimate Si integrated devices to further the evolution of information technology. In terms of device functions, single electron switching is the ultimate technology. In signal transmission, the ultimate goal is single electron transfer to the nearest neighbor site or long-distant sites. In fabrication technology, the final goal is the wafer-scale fabrication of atomically controlled device structures. There are two approaches available to achieving the latter: one is to refine lithographic techniques to achieve higher resolution and finer patterns (top-down approach), and the other is self-assembly based on the atomic structures of the Si substrate (bottom-up approach). Our aim is to create new concepts towards the ultimate Si integrated systems.

The Si Nanodevice Research Group is investigating the operation mechanism of Si single electron transistors (SETs) and their application to logic circuits, and performing fabrication process simulations. We have already demonstrated inverters and adders using SETs. We recently fabricated multi-valued logic circuits and a multi-bit adder as demonstrations of the wide range of functionality in SETs. Negative differential conductance in SETs has also been analyzed and applied to a new functional circuit. In single electron transfer devices (charge-coupled devices), we have succeeded to detect single-electron and single-hole transfer at room temperature. Operation mechanisms of SETs are being analyzed based on a structural model developed by the Nanostructure Technology Research Group. Si oxidation is the most important process in Si technology. We have shown that oxidation characteristics under various conditions can be explained using a universal model based on an atomic-level theory proposed by us.

The Nanostructure Technology Research Group is investigating nanofabrication techniques based on the top-down approach. We have established an ultrafine resist pattern formation process through improvement of electron beam lithography and optimization of resist materials and processes. We have proposed an original ultrafine patterning technique that uses supercritical fluid. Its outstanding performance was demonstrated in resist patterns with a high aspect ratio and ultrahigh density. A structural model of SETs fabricated in the Nanodevice Research Group has been established.

The Surface Science Research Group is investigating a bottom-up approach, aiming for Si nanointegration through surface structure control, nanostructure self-assembly, and carbon nanotube interconnection. For surface structure control, we are investigating atomic structures on step-controlled Si surfaces to control all atom positions on the surface. In nanostructure self-assembly, we have established strain engineering for control of the shape, distribution, and spacing of self-assembling Ge quantum nanostructures on Si surfaces. A new technique for functionalization of Si surfaces based on the incorporation of chemically synthesized nano-particles has been developed. In applications of synchrotron radiation, we have developed a technique for *in-situ* observation of growing surfaces and photoelectron microscopy for nanostructure characterization. During the past year, we put emphasis on our carbon nanotube project and started NEDO International Joint Research Grant Program. We have succeeded in bridging Si pillars by carbon nanotubes. Characterization of the electronic and atomic structures of the carbon nanotubes has also proceeded.

Single-Electron Multiple-Valued Logic

Hiroshi Inokawa, Akira Fujiwara, and Yasuo Takahashi
Device Physics Laboratory

Single-electron devices are quite suitable for multiple-valued logic, because the discreteness of the electronic charge in a Coulomb island can be directly related to multiple-valued operation. However, it is fairly difficult to construct the circuit only with single-electron devices because of their low voltage gain and the small applicable voltage. To solve this problem, we have proposed a hybrid device comprising a single-electron transistor (SET) and a MOSFET, and demonstrated the operation using devices fabricated by pattern-dependent oxidation (PADOX) process on a silicon-on-insulator (SOI) wafer.

The proposed device has a simple structure of a serially connected SET and MOSFET. A MOSFET is used to keep the SET drain voltage constant at a low enough value. As a result, the current flowing through the device is determined only by the SET input voltage; it is not affected by the output voltage. When the input and output terminals are shorted together, multipeak negative-differential-resistance is attained as two-terminal characteristics (Fig. 1). With a proper load device (a constant-current source in the case of Fig. 1), many stability points appear and these can be assigned to multiple-valued levels [1].

Figure 2 shows the input-output waveforms of a quantizer, which is a basic component of multiple-valued logic. The input voltage is transferred to the output terminal (V in Fig. 1) at the moment sampling pulses turn on the transfer-gate MOSFET (not shown in Fig. 1), and then quantized to the nearest stability point. We can see that the different voltage levels in the triangular wave are clearly quantized to stability points a ~ f.

With the proposed device, extremely compact multiple-valued logic can be constructed because circuit size is independent of the number of multiple-valued levels due to the periodic nature of the SET input-output characteristics. A new application field of single-electron devices can now be explored by the multiple-valued logic, as illustrated by an n-bit flash A/D converter whose size is proportional to n (in contrast to n^2-1 for conventional implementation) and an ultrahigh-speed multiple-valued adder without carry propagation [2].

[1] H. Inokawa et al., Appl. Phys. Lett. **79** (2001) 3618.
[2] H. Inokawa et al., International Electron Devices Meeting (IEDM) (2001) 147.

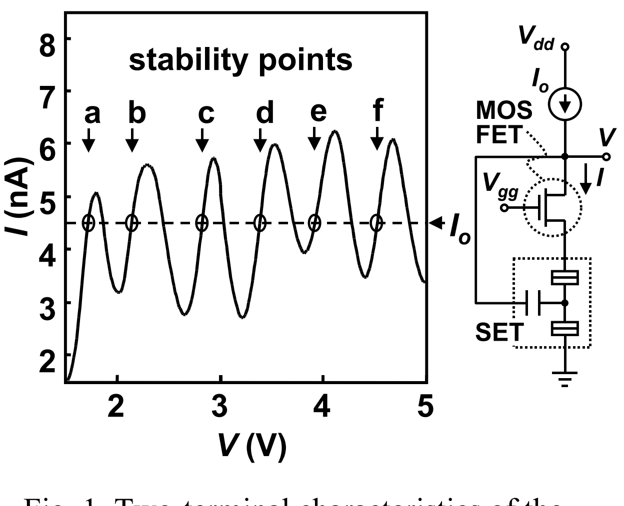


Fig. 1. Two-terminal characteristics of the SET-MOSFET negative-differential-resistance device operating at 27 K.

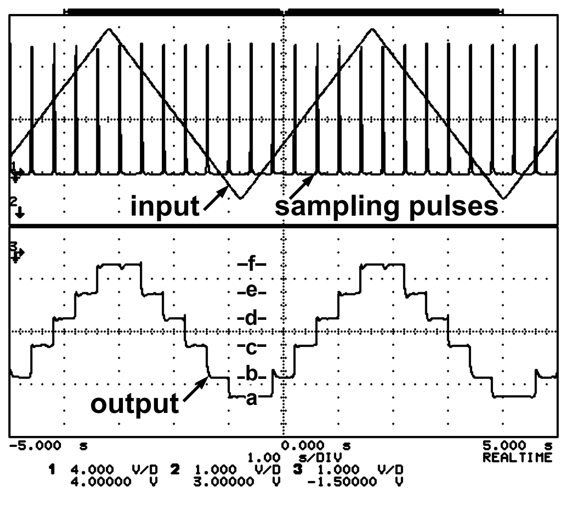


Fig. 2. Input-output waveforms of the quantizer.

Mechanism of Roughness Generation in Resists

Toru Yamaguchi and Hideo Namatsu
Device Physics Laboratory

Resist patterns less than 10 nm wide are indispensable for the fabrication of nano-structures, such as single-electron transistors. To form these patterns with high accuracy, we must reduce the edge roughness of resist patterns. We have already clarified that the roughness is generated through a dissolution process, which we call aggregate extraction development. Polymer aggregates 20-30 nm in size are naturally contained in resist films. These aggregates are extracted one by one during development. They appear on the pattern surface, causing roughness. The aggregate extraction development was found to strongly depend on the size of developer molecules. Thus, we can suppress it by using a developer molecule of optimum size.

Figure 1 shows atomic force microscope (AFM) images of a resist surface during development. Surface morphology differs largely with varying developer molecule size. For hexyl acetate, which is usually used for high-resolution pattern formation, many aggregates appear on surface [Fig. 1(c)]. For ethyl acetate, however, hardly any aggregates are observed [Fig. 1(a)].

In the dissolution of resist polymer, penetration of developer molecules into polymer matrix is a limiting step. Developer molecules penetrate through voids, so-called free volume, which are regions not occupied by polymer molecules. Therefore, the solubility of polymer aggregates is determined by the relative relationship between the size of voids in aggregates and molecular size of the developer. For a large developer molecule, such as hexyl acetate, polymers surrounding the aggregates dissolve first because the developer molecules easily penetrate the surrounding polymers, but they have difficulty penetrating the aggregates themselves. This is due to the difference in void size between the surrounding polymers and aggregates. As a result, the aggregate extraction development occurs and the surface becomes rough. For a small developer molecule, such as ethyl acetate, on the other hand, the aggregates themselves dissolve because developer molecules can easily penetrate them. As a result, the dissolution proceeds at the molecular level, not by aggregate extraction, and the surface becomes flat. For butyl acetate, the situation is in between because its size is between that of ethyl and hexyl acetate. These results indicate that there is an optimum developer molecule size that will reduce resist roughness by suppressing aggregate extraction development.

[1] T. Yamaguchi et al., Appl. Phys. Lett. **71** (1997) 2388.
[2] T. Yamaguchi et al., Proc. SPIE **3333** (1998) 830.

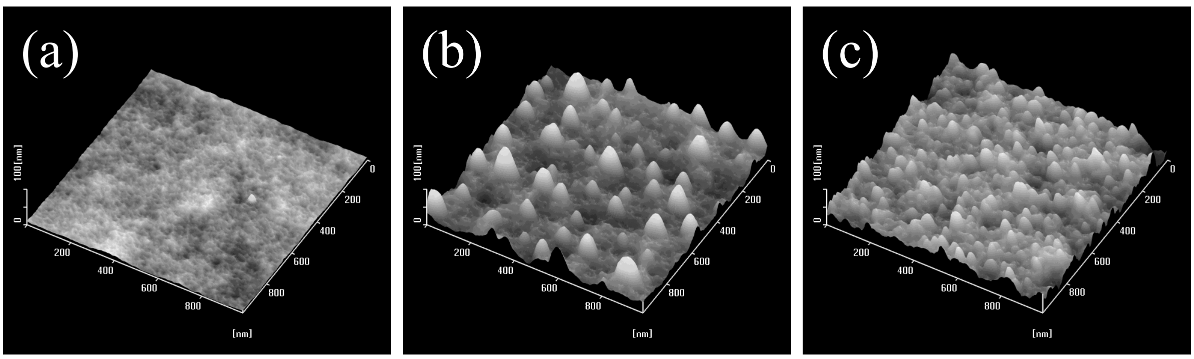


Fig. 1. AFM images of resist surface during development
Developer: (a) ethyl acetate, (b) butyl acetate, (c) hexyl acetate

Carbon Nanotube Interconnection

Yoshihiro Kobayashi, Takayuki Yamashita, Yoshikazu Homma, and Toshio Ogino
Device Physics Laboratory

In the application of semiconductor nanostructures to electronic devices, interconnections between individual nanostructures are very important for transmitting and processing signals. However, with traditional wiring technology, it is quite difficult to fabricate the connections between ultra-fine and dense nanostructures. To overcome this problem, we have proposed wafer-scale nanointerconnection based on carbon nanotube (CNT) self-assembly [1,2]. CNTs are promising for wiring and connecting nano-scale devices because of their peculiar mechanical and electrical properties. We have succeeded in fabricating a CNT network on an array of nanometer-scale Si pillars.

Figure 1 shows statistical distribution of CNT growth behavior analyzed from samples with Si pillar structure after CNT growth (see frontispiece). A CNT was grown by thermal chemical vapor deposition (CVD) with an iron catalyst. The CNT was observed to grow on 3/4 of the Si pillars and about half of the grown CNT bridged the pillars in an orderly manner. Such self-organized ordered bridging may be fairly anomalous since the CNT growth is ordinarily postulated to be random in the thermal CVD process. We have proposed a bridging growth mechanism where CNTs vibrate within a limited direction around a pillar and "search" for a neighboring pillar to stick to. The structure of the CNT was characterized by micro-Raman spectroscopy in order to confirm this mechanism. Figure 2 compares the Raman spectra from a pillar-fabricated region and a flat region containing no pillars. The Raman bands at 1316 cm^{-1} originate from the lowering of the translational symmetry due to defects. The spectra show that the bridging CNTs are more defective than those on the flat region, although the bridging CNTs are observed to grow in linear manner and are supposed to be less defective. This suggests that defects are formed by the vibration of CNTs during bridging growth, which agrees with our growth mechanism.

[1] Y. Homma et al., Jpn. J. Appl. Phys. **41**(2002) L89.
[2] Y. Homma et al., Physica B *in press*.

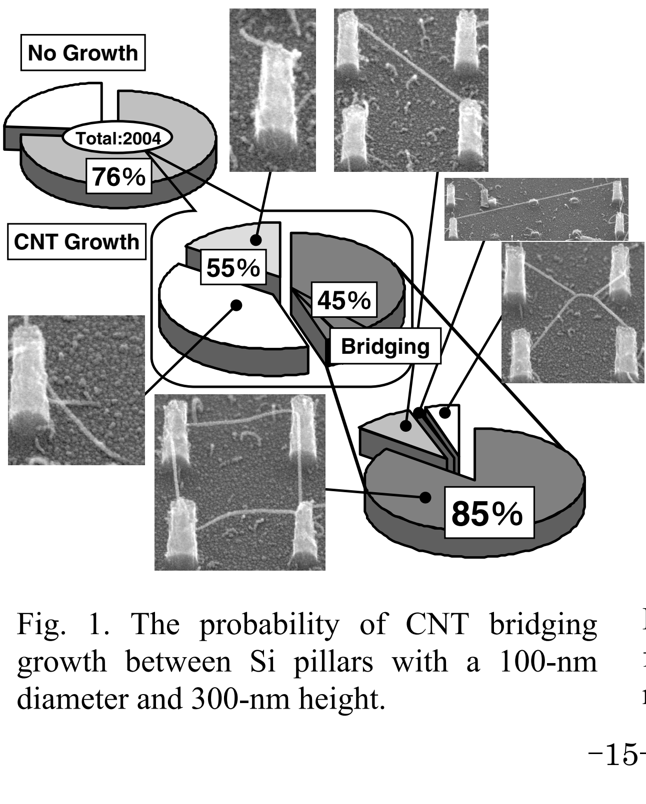


Fig. 1. The probability of CNT bridging growth between Si pillars with a 100-nm diameter and 300-nm height.

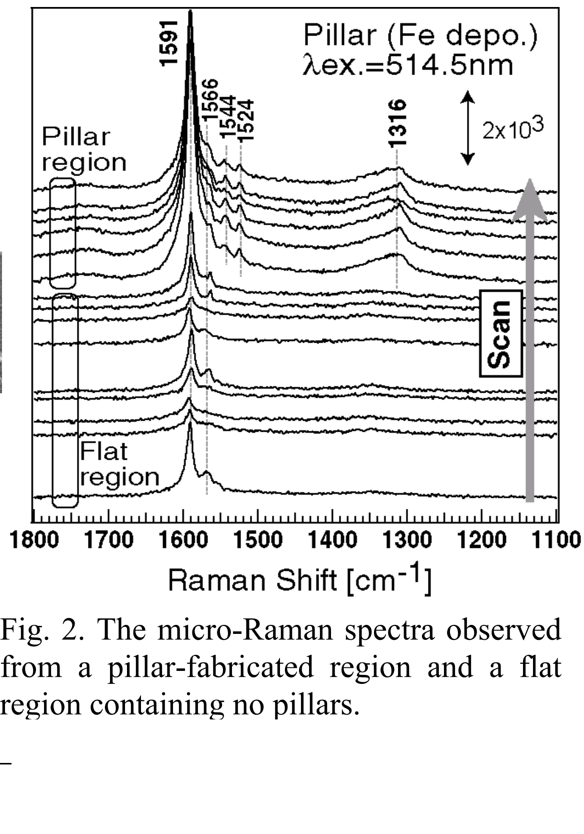


Fig. 2. The micro-Raman spectra observed from a pillar-fabricated region and a flat region containing no pillars.

Nanoparticles for Multi-Functionalization of Silicon: A Plug and Play Approach

K. Prabhakaran and T. Ogino
Device Physics Laboratory

Fabrication of nanostructures and their functionalization is essential to realize nanometre sized devices. However, problems with the poor controllability of the size, shape, spatial distribution and the functionality itself have been posing formidable challenges. This underlines the need to develop alternative processes such as self-organization and other nature-driven processes. Here, we demonstrate a novel approach whereby, externally synthesized nanoparticles are introduced on to the silicon wafer which is followed by manipulation of surface chemical bonds to introduce a variety of functionalities. Since the particles are synthesized externally this approach enables better control of various parameters.

Fe_2O_3 nanoparticles are introduced onto a device quality silicon wafer from a suspension in ethanol through an ultrasonic bath. The samples are dried and loaded into an ultrahigh vacuum chamber equipped with photoelectron spectrometer for monitoring the nature of the surface species. On annealing the samples, the oxygen atoms change the bonding partner from Fe to Si and desorbs as monoxide. This results in the complete reduction of the iron oxide particles to iron at around 760°C. These particles impart a soft-ferromagnetic property to silicon as shown in figure 2. On depositing a thin layer of silicon onto this sample, followed by annealing at 550°C, the sample exhibits light emission property. Figure 3 shows the photoluminescence spectrum obtained from this sample. In summary, we could introduce multiple functionality to silicon by treating it with nanoparticles, followed by manipulating the surface chemical bonds.

[1] T. Ogino et al., Accoun. Chem. Res. **32** (1999) 447.
[2] K. Prabhakaran et al. Advanc. Mater. **13** (2001) 1859.

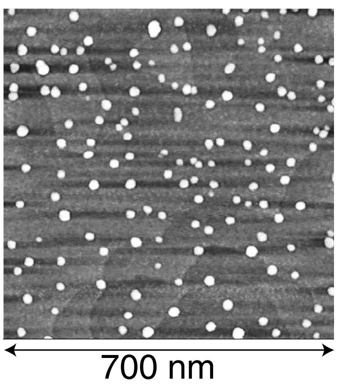


Fig.1. AFM image of Si sample treated with the particles followed by annealing in UHV. Fe articles of uniform size and shape are observed.

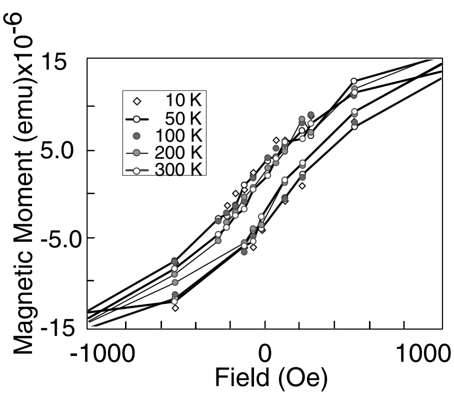


Fig. 2. Magnetization data from the particle treated Si showing hysterersis. Inset shows the variation of coercivity.

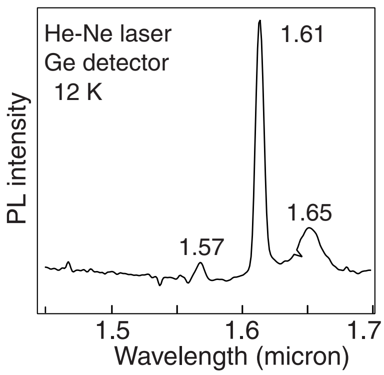


Fig. 3. PL spectrum recorded from the particle treated Si exhibiting light emission.

Overview of Material Science Research

Hideaki Takayanagi
Materials Science Laboratory

The Materials Science Laboratory (MSL) aims at producing new materials by controlling the arrangement and coupling among atoms and molecules. By producing such materials, MSL also aims to discover new quantum phenomena and to create new concepts. Toward these goals, the following four MSL groups investigate a wide variety of materials, from inorganic matter, such as semiconductors, to organic matter, such as neurotransmitters. The important feature of MSL is the effective sharing of nanofabrication and measurement techniques developed originally in each group.

Molecular and Bio-Science Research Group
Creating new organic materials based on the manipulation of single molecules, and researching information processing devices based on neural functions.

Superconducting Thin Films Research Group
Creating new high-Tc superconductors and applications to microwave communication using the molecular beam epitaxy method.

Superconducting Quantum Physics Research Group
Creating a quantum computer using superconductor, and creating new magnetic devices using quantum dot arrays.

Spintronics Research Group
Controlling the spin degree of freedom in a semiconductor and achieving new device functions in future electronics.

The four major results obtained in fiscal year 2001 are as follows.

1. The neuronal responses in rat hippocampus induced by low magnesium content. By measuring the spatial distribution of electrical activities using a special microelectrode array, it is found that electrical bursts became highly active in a magnesium-free medium. This indicates that magnesium ion could play a major role of neural activities in rat hippocampus.
2. In-situ MgB_2 thin film growth by the molecular beam epitaxy (MBE) method. MgB_2 has the highest superconducting transition temperature among non-oxide materials and is a promising for applications. The in-situ growth of MgB_2 films without annealing at elevated temperatures is substantial progress toward the fabrication of Josephson junctions.
3. A single shot readout of states in a flux quantum bit (qubit) with a superconductor ring. This could be the basis for the creation of a quantum computer using superconductor. The readout of the states is performed with sufficient accuracy by a DC-SQUID (superconductor quantum interferometer) aligned closely to the qubit.
4. A novel spin-filter device that has almost 100 % spin-filtering efficiency. The proposed device consists of a triple-barrier structure made up of nonmagnetic semiconductors. Electrons with a specific spin state are extracted by adjusting the emitter-collector bias voltage.

The details of these accomplishments will be described in the following pages.

Neuronal Responses in Rat Hippocampus Induced by Low Magnesium

Keiichi Torimitsu, Nahoko Kasai, and Yasuhiko Jimbo
Materials Science Laboratory

Magnesium ion has been known to play an important role in biochemical processes and development. However, its role in neural processes is still unclear. In this research, we focused on the effect of magnesium ion on the neural activities in rat hippocampal neurons. The neuronal responses, such as electrical bursts and glutamate release were investigated in rat hippocampus under low magnesium conditions. Measurements have been carried for dissociated cell cultures and slice preparations. Electrical bursts were measured using a 64-channel ITO microelectrode array. The size of the electrode was 10–50 μm each side. The array was fabricated with lithographical techniques and directly connected to 64-channel amplifier. Using this array, spatial distribution of the electrical activities could be measured. Transient changes of glutamate release were measured using an enzyme-based electrochemical detection method. The method includes glutamate oxidase, horseradish peroxidase and mediator polymer. They were placed on each microelectrode. Hippocampal neurons including slices were obtained from either P2 or P8 Wistar rat and cultivated them on a culture dish or a porous membrane for 7-14 days.

Electrical bursts turned to be highly active in a magnesium-free medium (MGF). A transient increase induced by the MGF was detected in the glutamate concentrations in the CA1, CA3 and dentate gyrus within a few minutes. Intracellular Ca concentration was also increased transiently. The NMDA receptor antagonist, MK801 suppressed the increase only in the CA1, but not in the CA3 and dentate gyrus. The results may indicate the diversity of NMDA receptor distribution and its dynamics in the hippocampus. Magnesium ion could be a key in the control of the neural activities in rat hippocampus.

[1] N. Kasai et al., Neurosci. Lett. **304** (2001) 112.
[2] K. Torimitsu et al., Gordon Res. Conf. **3** (2002).

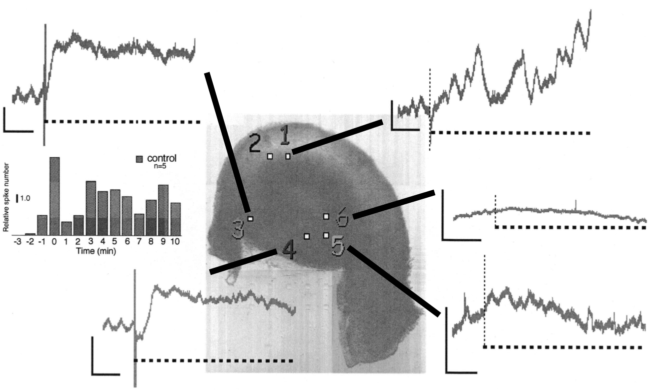


Fig. 1. Glu profiles at different positions and spike numbers in a rat hippocampal slice

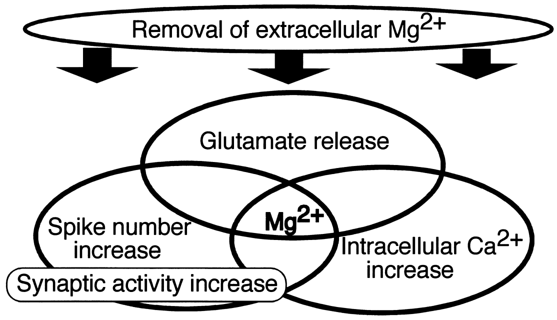


Fig. 2. Glutamate release and Mg.

In-situ Growth of Superconducting MgB_2 Thin Films.

Kenji Ueda and Michio Naito
Materials Science Laboratory

The recent discovery of superconductivity at 39 K in MgB_2 [1] has generated great interest in both basic science and practical applications. MgB_2 has the highest superconducting transition temperature (T_c) among non-oxide materials and its T_c is close to that of $La_{2-x}Ba_x$(or Sr_x)CuO_4, which were the first high- T_c superconductors. The T_c is slightly higher than the theoretical upper limit predicted for phonon-mediated superconductivity, which had been widely accepted until the discovery of superconducting cuprates. Therefore it is important to clarify the superconducting pairing mechanism of MgB_2, for which tunneling spectroscopy on the clean surface of thin films of MgB_2 should provide the most definite evidence. With a view to superconducting electronics applications, the thin film form of MgB_2 is also required. MgB_2 is a promising material for preparing Josephson junctions because it has a simpler crystal structure, fewer material complexities, and a longer coherence length (~ 5 nm) than cuprates in spite of its lower T_c. This scientific and practical interest triggered intensive efforts to prepare high-quality thin films of MgB_2.

The preparation of thin films of this rather simple intermetallic compound is impeded by the large difference between the vapor pressures of Mg and B. Therefore, most initial efforts employed the "two-step synthesis" in which amorphous B or Mg-B composite precursors are annealed at elevated temperatures with excess Mg in a sealed tube. However, this method is unsuitable for the fabrication of Josephson junctions or multilayers [2]. We used a different approach to avoid this problem and have recently succeeded in preparing the first ever as-grown MgB_2 films by using molecular beam epitaxy [3]. This success was achieved by reducing the growth temperature to as low as 300°C. The T_c is 35 K, which is close to the T_c of bulk MgB_2. The in-situ growth of MgB_2 films should enable substantial progress to be made toward the fabrication of Josephson junctions.

[1] J. Nagamatsu et al., Nature **410** (2000) 63.
[2] K. Ueda, M. Naito, Studies of High Temperature Superconductors, in press.
[3] K. Ueda, M. Naito, Appl. Phys. Lett. **79** (2001) 2046.

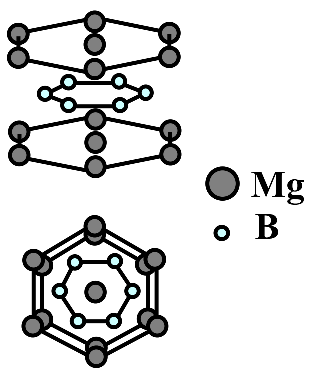


Fig. 1. Crystal structures of MgB_2.

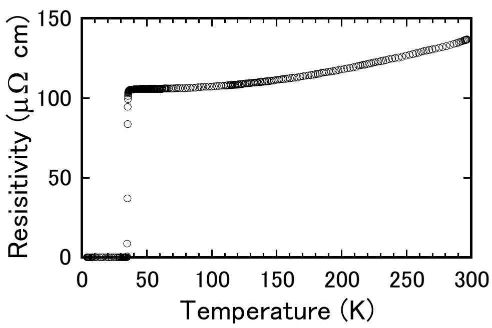


Fig. 2. Temperature dependence of resistivity of MgB_2 thin film.

Readout of Superconductor Quantum Bit

Hirotaka Tanaka, Siro Saito, *Masahito Ueda, and Hideaki Takayanagi
Material Science Laboratory
*NTT Research Professor, Tokyo Institute of Technology

A quantum computer is expected to perform fast parallel computation. Realizing a quantum bit (qubit), which is a basic element of a quantum computer, requires the ultimate controllability of the quantum system. We achieved a single shot readout of states in flux qubit with superconductor ring. Thanks to recent developments in nanotechnology, we have come close being able to control quantum states, which is a new paradigm of physics. The flux qubit has two fundamental quantum states that have current circulating in clockwise and counterclockwise directions. The readout of the states is performed by a DC-SQUID (superconductor quantum interferometer) aligned close to the qubit (see Fig.1). The DC-SQUID can detect the magnetic flux generated by qubit circulating current. We experimentally analyzed the readout characteristics of the flux qubit and found that our DC-SQUID is capable of reading out the qubit state with sufficient accuracy (see Fig. 2).

The quantum state has so far been used to explain behavior of individual atoms, electrons and so on. But in superconductor ring, the quantum state is carried by more than a millions of Cooper-pairs. Therefore, dynamics of this system are called macroscopic quantum phenomena and are often discussed as regards the manifestation of Schrödinger's cat. This means that the mechanism of this system is of interest not only from computational viewpoint but also from physical aspects.

[1] H. Tanaka et al., Physica C **368** (2002) 300.
[2] H. Tanaka et al., Supercond. Sci. Techonol. **14** (2001) 1161.
[3] H. Takayanagi et al., Proc. of Jubilee Nobel Symposium (Dec. 2001,Göteborg Sweden), to be published in Physica Scripta.

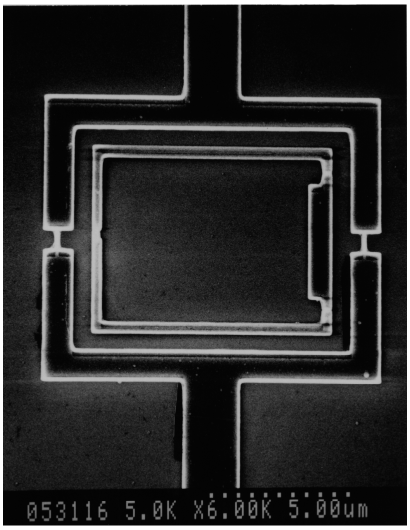


Fig.1. SEM (scanning electron microscope) picture of the qubit and DC-SQUID. The square inside is the qubit. The number of Josephson junctions are two in the qubit and three in the DC-SQUID. The Josephoson junctions have 1-5 nm thick aluminum oxide.

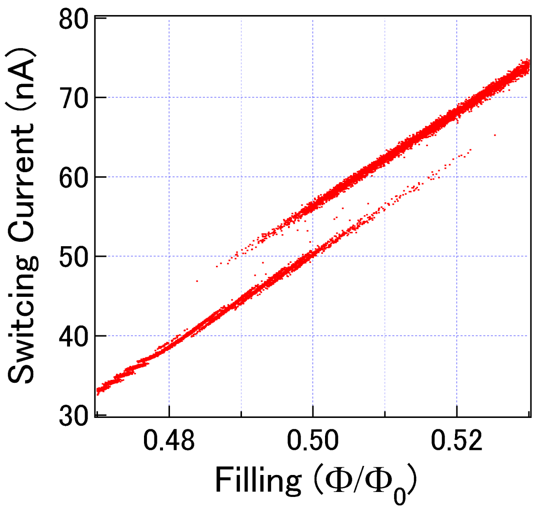


Fig.2. The readout characterinstics of the DC-SQUID. We clearly find the two lines that correspond to different qubit states. We changed the external magnetic field, which changes qubit parameter. This readout characteristics match the theoretical result. (See also the color front page.)

Proposal of a Spin-Filter Device using Nonmagnetic Semiconductors

Takaaki Koga and Junsaku Nitta
Materials Science Research Laboratory

Exploration of the spin degree of freedom in addition to the charge degree of freedom is considered to be a key strategy for the realization of new device functions in the future electronics. The research topics that have been pursued thus far from this point of view include (i) the spin injection experiment from a ferromagnetic metal to a semiconductor, (ii) the electric control of the spin precession in a two-dimensional electron gas that is confined in a nonmagnetic semiconductor quantum well (QW), (iii) the magnetic control of electron spins using diluted magnetic semiconductors. Recently, we have proposed a novel spin-filter device that combines the spin-orbit effect due to the built-in electric fields in the heterostructure and a triple barrier resonant tunnel diode [1]. This spin filter, which has almost 100 % spin-filtering efficiency, is unique in a sense that it does not use magnetic properties of materials. This device, therefore, can be fabricated using nonmagnetic semiconductors only. Possible applications of the device include the read-write devices for the information stored in spin qubits or/and magnetic random access memories.

The proposed device consists of a triple barrier structure, where $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ are used for the QWs and the barrier layers, respectively (See Fig. 1). In addition, the potential profile of the device has a particular mountain-like shape as shown in Figs. 1(b)(c), which is a result of proper *n* doping in barriers 1 and 3 and *p* doping in barrier 2. Because of this particular potential shape, the resonant tunneling levels that are formed in the first and second QWs (denoted as wells 1 and 2) experience spin splittings in a way they reflect the positive and negative electric fields induced within wells 1 and 2, respectively. We can, then, extract electrons with a specific spin state by adjusting the emitter-collector bias voltage V_{EC} properly. Shown in Fig. 2 are the calculated *I-V* curves of the proposed device for three different device structures, using the transfer matrix method. We see that the separation of the spin-split *I-V* curve peaks is roughly proportional to the magnitude of the potential slope within the wells.

[1] T. Koga, J. Nitta, H. Takayanagi, and S. Datta, Phys. Rev. Lett. **88** (2002) 126601.

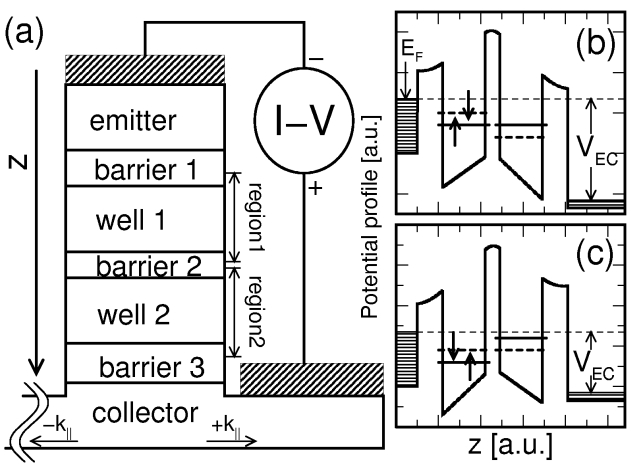


Fig. 1. Schematic diagram of the proposed spin-filter device.

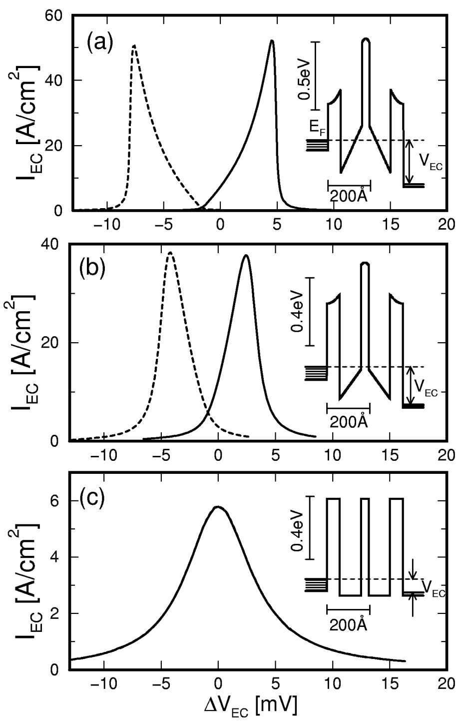


Fig. 2. *I-V* characteristic of the proposed device.

Overview of Quantum Physics and Electronics Research

Takaaki Mukai
Physical Science Laboratory

Our research in the fields of quantum physics and electronics, which is based on semiconductor nano-structures fabricated by high-quality semiconductor crystal growth and advanced device fabrication techniques, focuses on quantum electronic state control, carrier interactions and wide-bandgap semiconductor physics. Our aim is the development of innovative semiconductor devices. Quantum Solid State Physics Research Group and Wide-Bandgap Semiconductor Research Group are working in the following areas.

Quantum Solid State Physics Research Group

(1) Carrier interactions in low-dimensional semiconductor heterostructures (carrier interactions in bilayer systems, interactions between nuclear-spin and conduction electrons).
(2) Quantum electronic state control in quantum dot systems (spin control & carrier dynamics of quantum dots, fundamental properties of solid-state quantum computers).
(3) Semiconductor nano-mechanical systems (fabrication and characterization) and nano-probing (direct nano-scale imaging of electronic states by low-temperature STM).

Wide-Bandgap Semiconductor Research Group

(1) High-quality GaN crystal growth by MOCVD and device processing technology.
(2) GaN semiconductor electronic/optical device physics (FET, HBT, LED and LD).
(3) Electron field emission in AlN cold cathode materials.
(4) High-quality diamond epitaxial growth and its characterization.

Major results obtained this fiscal year 2001 are reported in the following pages.

We have successfully measured the local density of states (LDOS) distribution by differential conductance measurement using scanning tunneling microscopy (STM) at low temperature. It is confirmed that the measured LDOS distributions of a semiconductor nanostructure coincides with the probability distributions of the zero-dimensional eigenstates. This clearly demonstrates that we can now directly observe the nano-scale phenomena predicted by quantum mechanics, as if we looked through a microscope.

Applying perpendicular magnetic field to two parallel layers of two-dimensional electron gases separated by a thin tunnel barrier (electron bilayer system), two sets of Landau levels, i.e., originating from the two subbands energetically separated by the tunneling gap, give rise to many level crossings. We found there exists a finite energy gap even at the level crossing point. This is a new class of integer quantum Hall effect which relies solely on interactions.

We fabricated light emitting diodes (LEDs) having AlGaN active layer whose possible emission wavelength covers from 200 to 360 nm, and demonstrated high output power of 10 mW, i.e., one order of magnitude larger output than previous reports, at 352 nm wavelength. Present external quantum efficiency is still low around 1 %, however, the internal quantum efficiency has already been high enough as large as 80 %. This demonstrates that nitride materials containing Al have strong potential for highly-efficient light emitting devices.

We fabricated Npn-type heterojunction bipolar transistor (HBT) applying our originally developed p-InGaN layer with high hole concentration to a base layer. The measured maximum current gain was as high as 20, which is a world-record for nitride-based HBT. This demonstrates that the crystal quality of our p-InGaN layer is good enough and wide-bandgap nitride semiconductors show promise for high-power electronic devices.

Imaging of Zero-Dimensional States in a Semiconductor Nanostructure

Kiyoshi Kanisawa, Yasuhiro Tokura, Hiroshi Yamaguchi, and Yoshiro Hirayama
Physical Science Laboratory

The recent remarkable progress in fabrication process technologies has enabled the fabrication of nanometer-scale devices. Because electronic properties in the nanometer-scale region are governed by quantum mechanics, the development of quantum devices and quantum computers requires understanding and utilizing the wave phenomena of electrons in nanostructures.

We have measured the local density of states (LDOS) distribution by differential conductance (dI/dV) measurement using scanning tunneling microscopy (STM) at low temperatures [1]. We imaged the electron wave characteristics of conduction electrons, as well as the Friedel oscillation of two-dimensional electron gas (2DEG), at the semiconductor surface of indium arsenide (InAs) thin film.

Using this technique, we imaged the LDOS of zero-dimensional (0D) electron waves confined in a semiconductor nanostructure [2]. Figure 1 shows an STM image and schematic illustration of a semiconductor nanostructure, a so-called stacking fault tetrahedron. We found that when the structure size is comparable to the electron wavelength, the nanostructure behaves as a 0D structure (a quantum dot) and confines 2DEG in the accumulation layer at the InAs surface. We also found that the LDOS distribution of a semiconductor nanostructure coincides with the probability distribution of the 0D eigenstates. Such LDOS distributions are observed at intervals of the 0D level separation. This is because electrons tend to exist at discrete energy levels due to the quantization in the nanostructure. When the electron energy coincides with the quantized levels, quantum mechanical resonance is observed as a higher LDOS in the nanostructure than that in the surroundings.

[1] K. Kanisawa, M. J. Butcher, H. Yamaguchi, and Y. Hirayama, Phys. Rev. Lett. **86** (2001) 3384.
[2] K. Kanisawa, M. J. Butcher, Y. Tokura, H. Yamaguchi, and Y. Hirayama, Phys. Rev. Lett. **87** (2001) 196804.

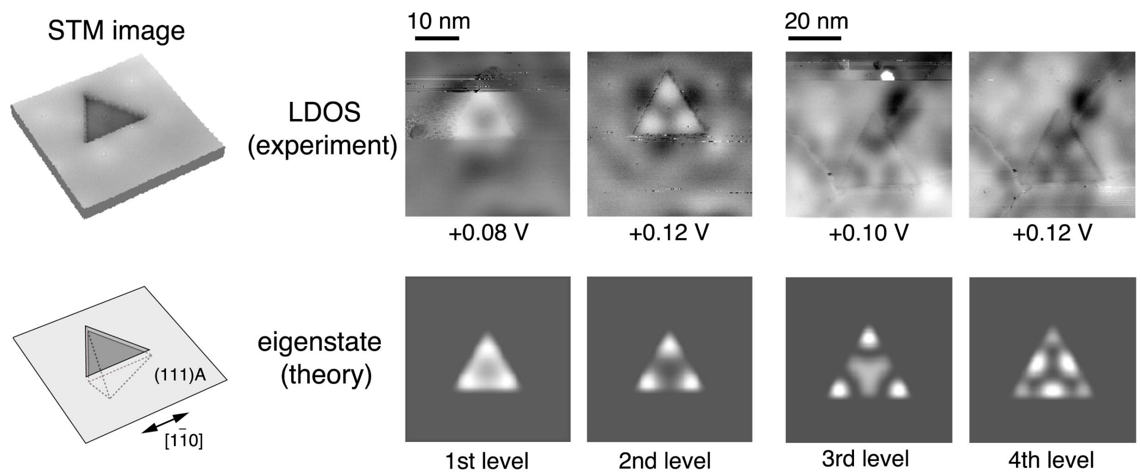


Fig. 1. STM image and schematic illustration of nanostructure [left]; LDOS images (experiment) and 0D eigenstates (theory) [right]. Brighter region indicates higher LDOS.

Pseudospin Ferromagnetic Order in Bilayer Electron Systems

Koji Muraki, Tadashi Saku, and Yoshiro Hirayama
Physical Science Laboratory

With advanced semiconductor growth techniques, it is possible to prepare two layers of two-dimensional electron gases separated by a thin tunnel barrier of a few nanometer thickness. Such systems, referred to as bilayer electron systems, allow one to tune the strengths of electron-electron interactions and tunneling between two layers, and exhibit novel physical properties that can not be achieved in a single layer. In particular, perpendicular magnetic fields enhance the electron-electron interactions by quenching the kinetic energy of electrons into discrete Landau levels. In this study, we reveal that the electron system exhibits a ferromagnetic order in particular situations when two Landau levels coincident at the Fermi energy (E_F) are regarded as up and down states of virtual spin (pseudospin).

We have fabricated a novel GaAs/AlGaAs quantum-well (QW) structure having both front gate and n^+-GaAs back gate to control the total electron density, n_s, and the potential symmetry independently [1, 2]. We employ a 40-nm wide single QW, which involves two occupied subbands with symmetric (S) and antisymmetric (A) wave functions and therefore behaves effectively like a bilayer [Fig. 1(a)]. When a perpendicular magnetic field, B, is applied, two sets of Landau levels originate from the two subbands, giving rise to various level crossings [Fig. 1(b)]. The energy diagram and the level crossings can be confirmed by measuring the magnetoresistance as a function of B and n_s while keeping the QW potential symmetric [Fig. 1(c)]. Activation measurements reveal that, at Landau level filling factor ν = 3 and 4, there is a finite energy gap even when two levels cross at E_F [Fig. 2(a),(b),(c)]. This energy gap shows the existence of a ferromagnetic order in the electron system, which suppresses the pseudospin flip and hence a dissipative current. This is a new class of integer quantized Hall effect which relies solely on interactions.

[1] K. Muraki, N. Kumada, T. Saku, and Y. Hirayama, Jpn. J. Appl. Phys. **39** (2000) 2444.
[2] K. Muraki, T. Saku, and Y. Hirayama, Phys. Rev. Lett. **87** (2001) 196801.

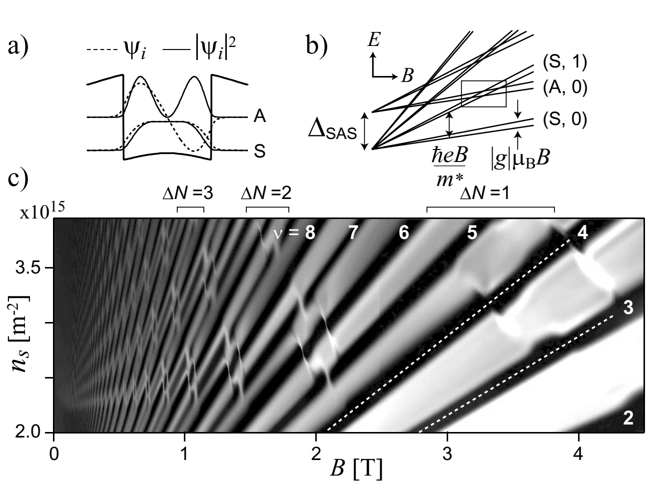


Fig. 1. (a) calculated wave functions for the single QW. (b) Landau level energy diagram in a bilayer system. (c) Gray-scale plot of magnetoresistance R_{xx} at 50 mK. Dark regions represent small values of R_{xx}.

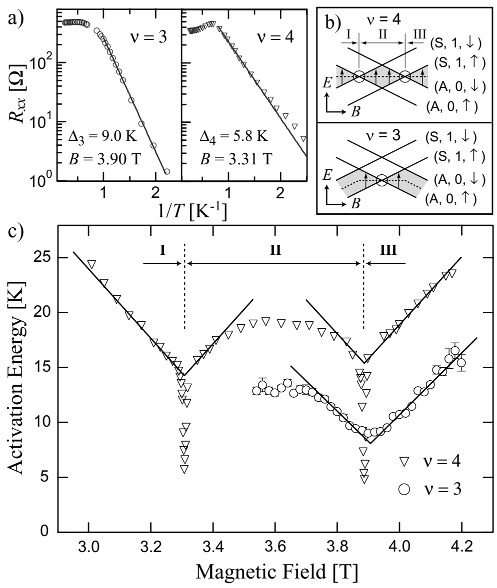


Fig. 2. (a) R_{xx} vs $1/T$. (b) energy level diagram near the crossings for ν = 3 and 4. (c) Activation energy as a function of B.

Npn-type InGaN/GaN Nitride Heterojunction Bipolar Transistor (HBT)

Toshiki Makimoto, Kazuhide Kumakura, and Naoki Kobayashi
Physical Science Laboratory

Wide-gap nitride semiconductors are promising materials for electronic devices that require high power and/or operate under high temperatures. On the other hand, a heterojunction bipolar transistor (HBT), a kind of electronic devices, is suitable for high-power devices due to high breakdown voltages, high current densities, and good threshold voltage uniformity. Therefore, a nitride HBT is a promising electronic device in terms of both materials and devices. However, there are few reports about nitride HBTs with high common-emitter current gains. In the previous reports, p-GaN was used for a base layer of a nitride HBT and there are two major problems for the conventional p-GaN. One is its high resistivity and the other is its severe damage induced by HBT fabrication process. To solve these two problems, we have developed on p-InGaN layers and found that these p-InGaN layers show high hole concentrations above 10^{19} cm^{-3} at room temperature, meaning that their resistivity is much lower than that of the conventional p-GaN [1]. Furthermore, we have also found that these p-InGaN layers are less damaged by the process [2].

In this work, we have applied the low-resistivity and less-damaged p-InGaN layer to a base layer of a nitride HBT for the first time. Figure 1 shows an Npn-type InGaN/GaN nitride HBT structure. For a collector layer, wide-bandgap GaN was used instead of InGaN to increase a breakdown voltage. A graded InGaN layer was inserted between base and collector layers to obtain higher current gains. Figure 2 shows the common-emitter current-voltage (I-V) characteristics at room temperature. From these characteristics, the maximum current gain was as high as 20, meaning that the crystal quality of this p-InGaN layer is relatively good [3,4]. Furthermore, a high breakdown voltage over 20 V has been obtained due to wide bandgap GaN collector. These device characteristics will be improved further by reducing dislocation densities and process damage.

[1] K. Kumakura et al., Jpn. J. Appl. Phys. **39**, (2000) L337.
[2] T. Makimoto et al., J. Cryst. Growth **221**, (2000) 350.
[3] T. Makimoto et al., Appl. Phys. Lett. **79**, (2001) 380.
[4] T. Makimoto et al., phys. stat. sol. (a) **188**, (2001) 363.

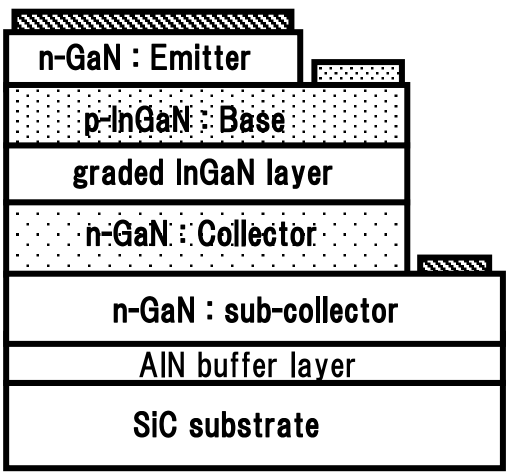


Fig. 1. Schematic structure of an InGaN/GaN nitride HBT.

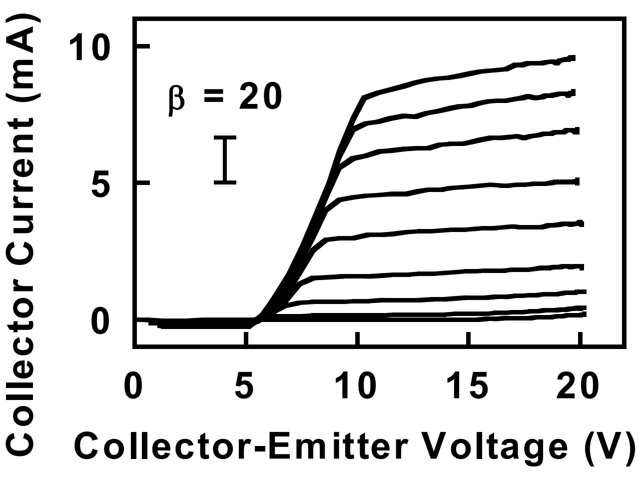


Fig. 2. Common-emitter current-voltage (I-V) characteristics at room temperature.

AlGaN-based Light Emitting Diodes

Toshio Nishida and Naoki Kobayashi
Physical Science Research Laboratory

Aluminum gallium nitride (AlGaN) is a wide band-gap semiconductor having optically direct transition. Therefore, it will provide solid-state ultraviolet (UV) light sources in the wavelength range of 200 – 360 nm. Such UV light sources have a wide variety of application fields, including lighting, displays, spectrofluometry, photo-catalytic processes, and high resolution optics.

For efficient light emission or, in other words, radiative recombination, the introduction of quantum well (QW) structure is desirable. We have, so far, clarified that suppressing the internal polarization field in nitride heterostructures can enhance radiative recombination. To improve the performance of UV light emitting diodes (LEDs) consisting of the AlGaN material system, we introduced a short period alloy superlattice (SPASL) for the electrically conductive and optically transparent cladding layers and for high-Al-content current blocking layers to achieve effective current injection [1]. We also introduced high-quality GaN bulk substrate to suppress non-radiative recombinations at crystal defects [2].

The structure of the UV-LED has 2-nm-thick AlGaN single quantum well (SQW) as an active layer, which suppresses the internal polarization field. This active layer is sandwiched by n-type and p-type $Al_{0.3}Ga_{0.7}N$ current blocking layers, and by n-type and p-type SPASL ($Al_{0.16}Ga_{0.84}N$ / $Al_{0.2}Ga_{0.8}N$, 3nm period) cladding layers (Fig. 1). This device achieved a maximum output power of 10 mW at the emission wavelength of 352 nm (Fig. 2), which is higher than the previous record in this UV wavelength range by one order of magnitude. The highest external quantum efficiency is 1 %, and the estimated internal quantum efficiency is as high as 80 % [2], which is comparable to that of conventional LEDs in the visible wavelength range. Further, its emission spectrum is highly monochromatic without any significant deep level emissions in the visible range.

We have also demonstrated the efficient application of this short wavelength UV-LED to the excitation of fluorescence materials of the three basal colors (red, green, and blue) used in lighting and display devices [3].

[1] T. Nishida et al., Appl. Phys. Lett. **78** (2001) 3927.
[2] T. Nishida et al., Appl. Phys. Lett. **79** (2001) 711.
[3] T. Nishida et al., phys. stat. sol.(a) **188** (2001) 113.

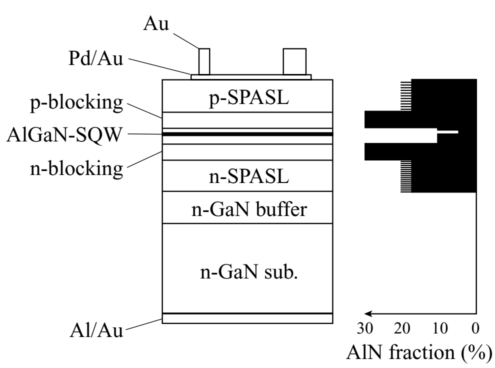


Fig. 1. LED structure.

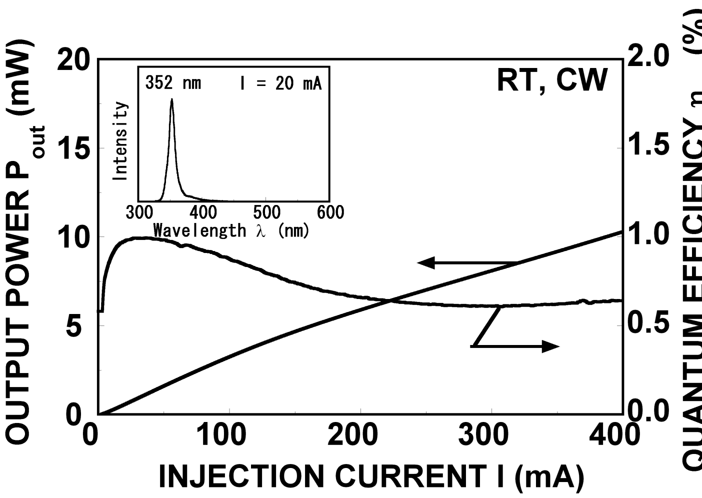


Fig. 2. Output power, efficiency, and the emission spectrum of the AlGaN-based UV-LED.

Overview of Quantum Optics and Optical Materials Research

Takaaki Mukai
Physical Science Laboratory

In the fields of quantum optics and optical materials we pursue our studies for the development of core-technologies that will innovate optical communications and optical signal processing as well as for the scientific progress of the field. Optical State Control Research Group, Ultrafast Optical Physics Research Group, Optical Device Physics Research Group and Photonic Nanostructure Research Group are engaged in the subjects listed below.

Quantum State Control Research Group
(1) Quantum communication and information processing (quantum cryptography/protocols, entanglement, and computing).
(2) Atom optics (Bose-Einstein condensation of alkali atoms).

Ultrafast Optical Physics Research Group
(1) High-irradiance, short-pulse soft X-ray generation from femtosecond laser-produced plasma and its application to materials science.
(2) Ultrafast laser pulse induced terahertz radiation and its application.

Optical Device Physics Research Group
(1) Coherent control of excitonic and spin states in quantum dots & wires.
(2) Optical properties in nitride-semiconductors and their device applications.
(3) Nano-scale fabrication process for photonic crystal materials.

Photonic Nanostructure Research Group
(1) Two-dimensional photonic crystal optical circuits on SOI substrate (line/point defects).
(2) Three-dimensional photonic crystal structures and organic photonic crystal lasers.
(3) Interaction between photonic nanostructures and materials (negative refraction, extremely-large group velocity dispersion).

Major results obtained this fiscal year 2001 are reported in the following pages.

We have proposed fault-tolerant simple quantum protocol for bit-commitment that is unbreakable by individual particle attacks. This is a successful example to extend the basic idea of quantum cryptography, i.e., ultimate security guaranteed by uncertainty principle, to several magic protocols involving signature schemes, two-party secure computation, and so on.

We demonstrated a cross-correlation technique for measuring an ultrashort soft x-ray-pulse shape using the rapid increase in Kr^+ ion density caused by optical-field induced ionization. This technique can be a breakthrough to greatly improve the highest temporal resolution of 1 ps realized so far by x-ray streak cameras.

Control of quantum mechanical superposition of an exciton in a single InGaAs quantum dot (QD) was demonstrated by irradiating successive optical pulses with precise delay-phase control. This demonstrates a phase rotation gate operation on the QD exciton as quantum bit and reinforces the potential of QD excitons in quantum logic application.

We first fabricated efficient single-mode optical waveguides that operate within a photonic bandgap wavelength, embedded in the two-dimensional photonic crystals on SOI substrates. We have directly measured the dispersion of photonic crystal waveguides, and clarified that they have extremely large group dispersion. These results show promise for ultra-small, highly- functional optical integrated circuits based on photonic crystal structures.

Quantum Magic Protocols

Kaoru Shimizu and Nobuyuki Imoto*
Physical Science Laboratory

Modern cryptography offers many functions such as authentication and signature schemes, beyond usual uses for secret communication. Its security, however, relies on an unproven assumption that solving some mathematical problems requires huge computational time longer than the age of universe. By contrast, quantum cryptography aims at performing security information processing through quantum-state manipulation of carrier particles such as photon and guaranteeing the ultimate security on the basis of uncertainty principle of quantum mechanics. The most successful example is quantum key distribution that makes it possible for distant two parties to distribute a secure cipher key. It is, however, difficult to extend the basic idea of quantum cryptography to several magic protocols involving signature schemes, two-party secure computation, and so on. Moreover, there have been clarified fundamental difficulties in some of these efforts.

Our research motivations are to clarify (i) what kinds of quantum magic protocol are possible in principle, and (ii) what kinds of advantage we can expect for magic protocols by use of quantum mechanics. So far we have obtained two positive theoretical results on these points. One is the proposal of quantum communication protocol for cipher-text transmission that allows repeated use of the same cipher key [1]. Another proposal is a fault-tolerant simple quantum protocol for bit-commitment that is unbreakable by individual particle attacks [2]. The former makes it possible for legitimate users to avoid security degradation in the cipher key by monitoring the status of the key. The latter is a magic protocol for giving a receiver any evidence of sender's bit choice without revealing the bit value and is secure against any kinds of individual particle attack that is only a feasible attack until quantum computer networks are developed. In comparison with conventional quantum bit commitment protocols, our proposed scheme is mathematically far simpler, more efficient in terms of transmitted photon number, and better tolerant of bit-flip errors. Figure 1 shows a four-path single-photon interferometer that is employed as a quantum communication channel. Quantum state of each propagating photon can be manipulated by controlling the interference patterns [1].

* NTT Research Professor, Soken,The Graduate University for Advanced Studies.

[1] K. Shimizu and N. Imoto, Phys. Rev. A **60** (1999) 157, Phys. Rev. A **62** (2000) 054303.
[2] K. Shimizu and N. Imoto, Phys. Rev. A **65** (2002) 032324.

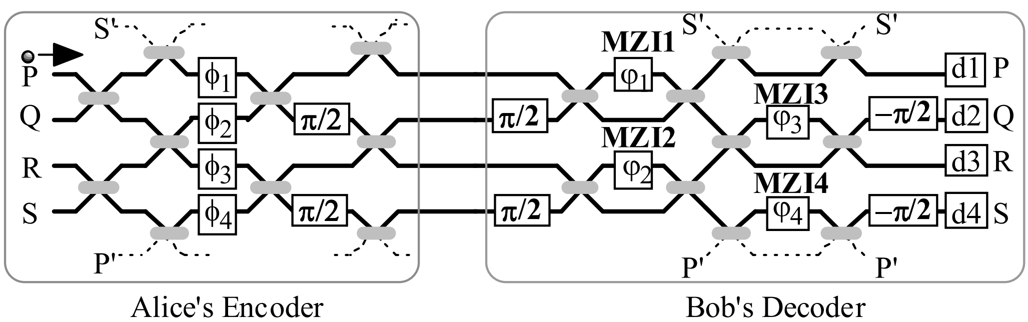


Fig. 1. Configuration of the four-path single-photon interferometer for the quantum channel.

Measuring an Ultrashort Soft X-Ray Pulse Shape

Katsuya Oguri, Hidetoshi Nakano, and Tadashi Nishikawa
Physical Science Laboratory

Recent developments in various ultrashort pulse x-ray sources based on a high-intensity femtosecond laser have made experimental demonstrations of time-resolved x-ray absorption and diffraction with picosecond to sub-picosecond resolution possible. The x-ray-pulse shape is one of the most important parameters because its duration limits the temporal resolution of this time-resolved x-ray spectroscopy. To date, an x-ray streak camera has usually been used for directly measuring x-ray pulses from nanosecond to picosecond, but its highest temporal resolution is currently about 0.9 ps. Therefore, to measure a sub-picosecond x-ray pulse, it is essential to extend the kind of correlation techniques usually used for measuring a femtosecond laser pulse to the x-ray region.

We demonstrated a cross-correlation technique for measuring an ultrashort soft x-ray-pulse shape using the rapid increase in Kr^+ ion density caused by optical-field induced ionization, which operates as an ultrafast x-ray-absorption switch [1]. Using this technique, we measured a soft x-ray-pulse shape at 15.6 nm emitted from W plasma produced by a 100-fs laser pulse. Figure 1 shows typical time-integrated spectra. A broadband soft x-ray emission from W plasma is shown in Fig. 1 (a). In the transmission spectrum through Kr gas (Fig. 1 (b)), three absorption lines for neutral Kr atoms can be clearly observed near 13.5 nm. When Kr gas was irradiated by the ionizing pulse 3 ps before the arrival of the soft x-ray pulse, several Kr ion absorption lines appeared clearly while the absorption of neutral Kr decreased considerably (Fig. 1 (c)). We plotted the differential transmittance at 15.6 nm, which correspond to the absorption line of Kr^+, as a function of the time delay between the laser and soft x-ray pulses (Fig. 2). The differential transmittance is the convolution of the soft x-ray pulse with the step-like change of the soft x-ray absorption. By fitting the integrated Gaussian function to the data, we found the full width at half maximum of the soft x-ray pulse to be 3.8 ps. This result agrees well with the duration measured with an x-ray streak camera thus confirming the feasibility of this technique. The most notable feature of this technique is that we can expect the temporal resolution to become shorter than the laser pulse duration, because the ionization is completed in the leading edge of the laser pulse.

[1] K. Oguri et al., Appl. Phys. Lett. **79** (2001) 4506.

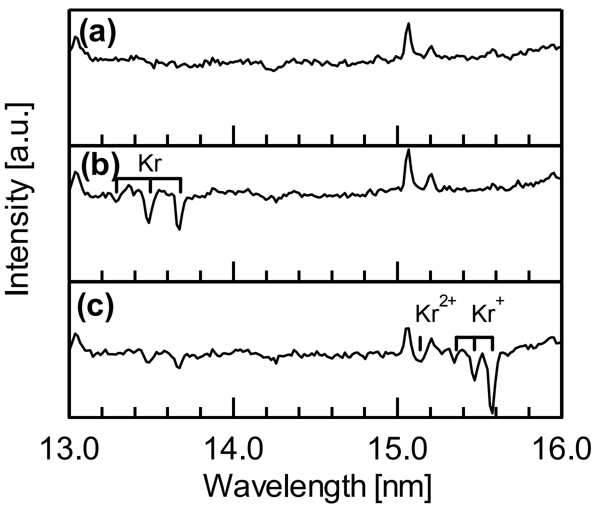


Fig. 1. Typical time-integrated spectra in the 13 –16 nm wavelength range.

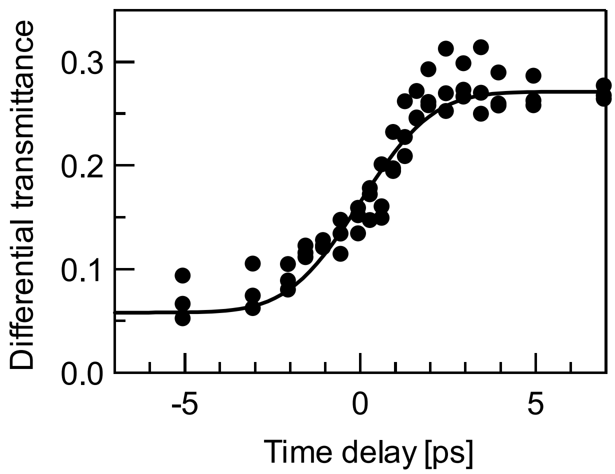


Fig. 2. Differential transmittance at 15.6 nm as a function of the time delay.

Quantum Gate Operation of Quantum Dot Exciton Qubit

H. Kamada and H. Gotoh
Physical Science Laboratory

Control of quantum mechanical superposition of an exciton in a single $In_xGa_{1-x}As$ quantum dot was demonstrated. Coherent control of a quantum mechanical system is an ultimate challenge, and it is essential toward realization of quantum computing. Rapidly growing maturity of nanofabrication technologies have made quantum two-level system in solids promising for such approaches. Exciton confined within mesoscopic dot is such a candidate: The similarity between atoms and QD excitons together with the long-lived coherence and the mesoscopically enhanced oscillator strength may offer a great opportunity of coherent manipulation of a well-defined single localized quantum system by optical field.

As an $In_xGa_{1-x}As$ quantum dot is exposed to electromagnetic radiation, the periodic oscillation of electric field of the light is imprinted to exciton polarization. While this coherent dipole oscillation persists, the periodic energy exchange between the light and the exciton representing light absorption followed by coherent stimulated light emission, results in a periodic exciton population oscillation: Or equivalently, the superposition of the exciton existence oscillates. This is Rabi oscillation, which was confirmed previously. It is then feasible to generate any superposition of the exciton two-level wavefunction in an isolated quantum dot with control of phase and strength of the light pulses. To demonstrate this, two-laser pulse excitation experiment with a precision delay control was undertaken. The first pulse induced the exciton dipole oscillation and created a 30-40 % superposition state (Fig.1). The second pulse delayed by 10 ps exactly in-phase with the first pulse added up the population/superposition to a value twice as large as that created by first one. In contrast, as the second pulse exactly out-of-phase to the first one erased the exciton population to null. Such results are summarized in Fig. 1. Apparently, this demonstrates a phase rotation gate operation on the quantum dot exciton as quantum bit and reinforces the potential of QD excitons in quantum logic application.

[1] H. Kamada, H. Gotoh, J. Temmyo, T. Takagahara, and H. Ando, Phys. Rev. Lett. **87** (2001) 246401.

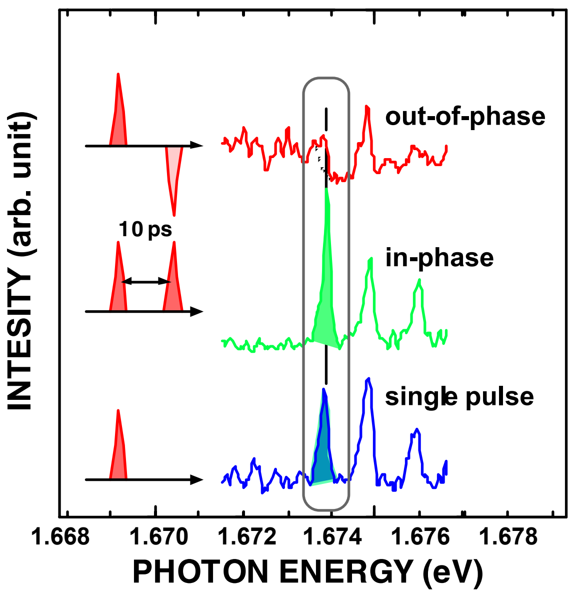


Fig. 1. Experimental demonstration of coherent control of exciton population by phase-locked optical pulse pair: The first pulse creates an exciton superposition that is either doubled or erased depending on the relative phase.

Photonic-Crystal Single-Mode Waveguide

Masaya Notomi, Akihiko Shinya, and Itaru Yokohama
Physical Science Laboratory

Photonic crystal is an artificial dielectric structure of which refractive index is periodically modulated with the wavelength-scale dimension, which can be fabricated by the state-of-the-art nano-fabrication technology. This crystal has a photonic band gap when a certain condition is satisfied, and then it becomes an exotic *photonic insulator* which rejects the propagation of light without any absorption. This unique feature is expected as a cutting-edge break-through technology for realizing future photonic large-scale integrated circuits (LSI) because we can confine the light in a ultrasmall volume by using this crystal.

With these motivations, we started the fabrication of Si-based photonic crystals with a strong collaboration with NTT Telecommunication Energy Laboratories by using e-beam lithography and dry etching, and have already reported a successful realization of two-dimensional photonic crystals on SOI substrates having a wide photonic band gap between 1.3 to 1.6 μm covering today's fiber communication wavelengths. Recently, we fabricated efficient single-mode optical waveguides that operate within a photonic band gap wavelength. In a photonic crystal having a gap, a line defect has a potential to serve as a tightly confined single-mode optical waveguide, but practically this was not an easy task especially for SOI-type photonic crystals. We have solved this problem by tuning geometrical structure of a line defect in various ways, as shown in Fig. 1 [1]. In addition, we have directly measured dispersion of photonic crystal waveguides for the first time, and clarified that they have extremely large group dispersion, and the traveling speed of light can be largely reduced down to 1/100 of the speed of light in air as shown in Fig. 2 [2]. This large reduction of traveling speed is a direct manifestation of tunability of light propagation in photonic crystals beyond the limitation of material itself. This tunability is especially important for high-speed photonic information processing and also for enhancement of light-matter interaction.

[1] M. Notomi et al., Electron. Lett. **37**, (2001) 243.
[2] M. Notomi et al., Phys. Rev. Lett. **87**, (2001) 253902.

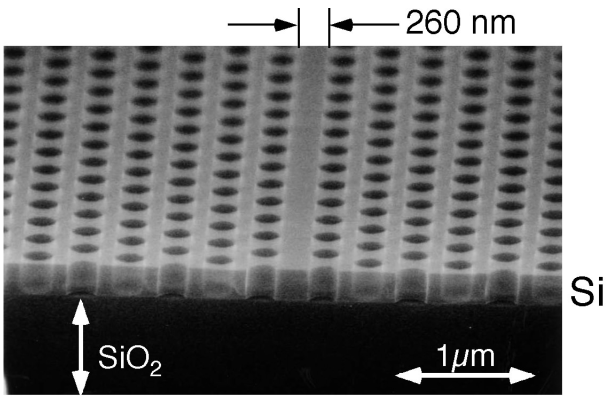


Fig. 1. SOI photonic-crystal single-mode optical waveguide.

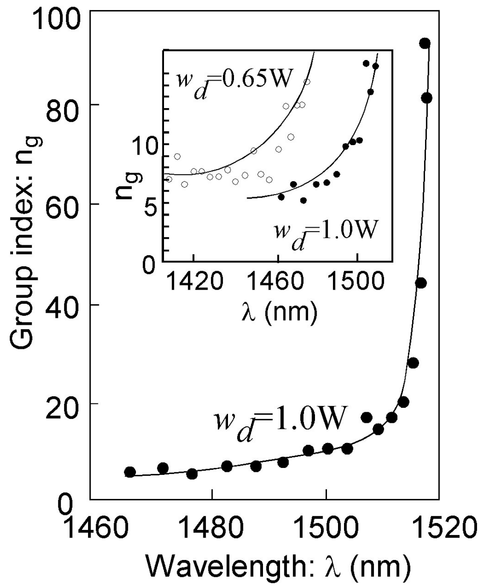


Fig. 2. Group dispersion of photonic-crystal waveguide (measurement). Group index versus wavelength.

Ⅱ. Data

International Symposium on Mesoscopic Superconductivity and Spintronics

The international symposium named MS+S2002 was held on March 4-6, 2002, at the NTT Atsugi R&D Center in collaboration with New Energy and Industrial Technology Development Organization (NEDO) and the Physical Society of Japan (JPS). A field of physics called "Mesoscopic Superconductivity" includes Andreev reflection, a superconductor/ferromagnet system, a π-junction, quantum coherence and a quantum bit. Spintronics, that is made from spin and electronics, includes spin-related transport phenomena and ferromagnetic semiconductors, etc. NTT Basic Research Laboratories has led both fields, and the symposium aspired to gather the leading scientists and discuss the most recent topics.

Dr. Sunao Ishihara, Director of NTT Basic Research Laboratories, opened the symposium with welcoming remarks. Next, Dr. Hideaki Takayanagi, NTT R&D Fellow, Executive Manager of NTT Basic Research Laboratories, gave a keynote address.

Oral sessions consisted of 51 presentations by invited speakers and contributed ones. Poster sessions had 62 presentations. Prof. J. Clarke of University of California, Berkeley, the inventor of a superconducting interference device (SQUID), gave a plenary talk entitled "The DC SQUID: From Traditional Designs to New Ideas for Quantum Measurement". This was followed by the observations of the quantum superposition and Rabi oscillations were discussed in a SQUID as well as an ultrasmall superconducting dot. The time-domain measurements of the Q-bit state were also reported by Chalmers University (Sweden) and Yale University. We reported one-shot measurement of the Q-bit state by a dc-SQUID.

One of the main subjects in Spintronics was the spin-injection effect. Prof. E. Rashba of MIT, who is famous for his pioneering work "Rashba effect", discussed that spin injection was the key to many new phenomena and applications in the field of the spin-polarized electron transport. In the symposium we proposed a spin filter that utilized Rashba effect in a resonant tunneling structure.

The participants were 190 people [companies and universities: 149 (overseas: 64, domestic: 126), NTT: 41]. Many participants were strongly impressed by the high quality of the presentations. The proceedings will be published in the special book by World Scientific. The symposium was recorded on videotape and the tape has been used for public relations.

Award Winner's List (Fiscal 2001)

The 4th Electronics Society Award (The Institute of Electronics, Information and Communication Engineers)	T. Mukai T. Saitoh Y. Yamamoto* *NTT R&D Fellow Stanford Univ.	"Pioneering Research on Semiconductor Optical Amplifiers"	Sept. 19, 2001
The EMS Award (20th Electronic Materials Symposium)	M. Kasu	"MOVPE Growth and Large Field Emission of Heavily Si-doped Aluminum Nitrides	Jun. 22, 2001
SLOW-MAG AWARD (Gordon Research Conference)	K. Torimitsu N. Kasai Y. Jimbo Y. Furukawa* *CREST	"Glutamate transients and neuronal bursts at multiple positions in a rat cortex and hippocampus induced by low magnesium"	Feb. 8, 2002

In-house Award Winner's List (Fiscal 2001)

NTT R&D Award	K. Kanisawa H. Yamaguchi Y. Hirayama Y. Tokura	"Direct Imaging of Electron Wave Phenomena in a Semiconductor"	Dec. 2, 2001
Award for Achievements by Director of Basic Research Laboratories	H. Namatsu	"Advanced Nanolithography Using Supercritical Fluid Technology"	Feb. 27, 2002
Award for Achievements by Director of Basic Research Laboratories	M. Notomi A. Shinya I. Yokohama	"Elucidation of Fundamental Optical Properties in 2D Photonic Crystals"	Feb. 27, 2002
Award for Meritorious Services by Director of Basic Research Laboratories	T. Yamaguchi	"Development of Chemical Management System with Barcode Readers"	Feb. 27, 2002
Award for Excellent Papers by Director of Basic Research Laboratories	A. Fujiwara	"Manipulation of Elementary Charge in a Silicon Charge-Coupled Device" Nature vol. 410, 560-562 (2001)	Feb. 27, 2002
Award for Excellent Papers by Director of Basic Research Laboratories	H. Kamada	"Exciton Rabi Oscillation in a Single Quantum Dot" Phys. Rev. Lett. vol. 87, 246401 (2001)	Feb. 27, 2002

List of Visitor's Talks (Fiscal 2001)

I. Device Physics

Date		Speaker	Affiliation "Topic"
June	1	Prof. Christian Teichert	University of Leoben, Austria "Self-organization of nanostructures in semiconductor heteroepitaxy"
June	19	Dr. David Fraboulet & Dr. Barbara De Salvo	CEA-LETI, France "About CEA-LETI and research on silicon single electronics in LETI"
Sept.	14	Ms. Ruth Child	University of Oxford, UK "Tunable mid-IR emission using a novel quantum dot-quantum well coupled system" "STM study of germanium quantum dots on patterned silicon surfaces as a function of growth time"
Sept.	14	Mr. Damiano Giubertoni	The Center for Scientific and Technological Research (ITC-irst), Italy "Solid state reaction in Ti-Si bilayers: new results from in situ measurements"
Oct.	17	Dr. Yuden Teraoka	Synchrotron Radiation Research Center, Japan Atomic Energy Research Institute "Oxidation reaction dynamics of Si(001) surfaces using supersonic O_2 molecular beams"
Nov.	1	Dr. Robin Williams	Institute for Microstructural Sciences, National Research Council, Canada "Ordered quantum dots for InAs/InP"
Nov.	22	Ms. Berta Guzman	Universidad Politecnica de Madrid, Spain "Simulation of SiO_2 build-up in silicon under oxygen bombardment"
Nov.	28	Dr. Satyban Bhunia	The University of Electro-Communications "Fabrication of a GaInP/GaAs heterojunction bipolar transistor (HBT) by MOCVD" "Real-time study of MOCVD growth process by using synchrotron x-ray source"
Dec.	18	Dr. Takashi Sekiguchi	Nanomaterials Laboratory, National Institute for Materials Science "Cathodoluminescence and its application to various semiconductors"

Dec.	18	Dr. Shigeo Tanuma	Nanomaterials Laboratory, National Institute for Materials Science “Calculation and measurements of electron inelastic mean free paths in solids”
Dec.	20	Prof. Mitsuhiro Katayama	Osaka University “Atomic-hydrogen-induced self-organization and hydrogen-surfactant effect on surfaces”
Feb.	22	Prof. Naoki Yamamoto	Tokyo Institute of Technology “Cathodoluminescence study of nano-structures in semiconductor epilayers”
Feb.	22	Dr. V. Grillo	Tokyo Institute of Technology “InAs/GaAs self assembled quantum dots study: emission, strain and morphology by HRTEM and CL-TEM”
Feb.	27	Dr. Kazuhiko Hayashi	Semiconductor Energy Laboratory Co., Ltd “Study on fabrication of nanometer-order structures on silicon surfaces and observation of their decay processes using scanning tunneling microscopy”
March	26	Prof. Yuji Takakuwa	Institute of Multidisciplinary Research for Advanced Materials, Tohoku University “In-situ observation of the initial stage of the silicon thermal oxidation by the real-time auger electron spectroscopy combined with the reflection high energy electron diffraction (RHEED-AES)”

II. Materials Science

Date		Speaker	Affiliation "Topic"
May	8	Prof. Eiichi Nakamura	The University of Tokyo “Highly effective chemical modification of fullerene – the course to metal-fullerene complex polymers”
June	18	Dr. P. M. Koenraad	Eindhoven University of Technology, The Netherlands “Analysis of single and stacked InAs quantum dots at the atomic level by cross-sectional STM”
June	18	Dr. Ronald Cron	CEA-Saclay, France “Electrical transport through one atom contacts”
Aug.	17	Prof. Tomoji Kawai	Osaka University “Nanotechnology toward artificial bio-information materials and devices”

Oct.	2	Prof. Rudolf Gross	Technical University of Munich, Germany “Physics and applications of superconducting and magnetic oxides”
Dec.	14	Dr. Larry A. Nagahara	Physical Sciences Research Laboratories, Motorola Inc., USA “Molecular-scale engineering: what is needed for success?”
Jan.	10	Dr. Mutsuhiro Shima	Massachusetts Institute of Technology, USA “Nanostructured magnetic materials for data storage applications”
Jan.	25	Dr. Duanlian	Tokyo Medical and Dental University “Cisplatin augments TNF-a cytotoxity by induction of apoptosis in glioblastoma cell lines”
March	15	Prof. Peter A. Gruenberg & Dr. D.E. Buergler	Institute of Solid State Research (IFF), The Research Centre Juelich, Germany “Structures of thin magnetic films separated by metallic or semiconducting interlayers: growth, structural, magnetic and magnetotransport properties”

III. Quantum Electron Physics

Date		Speaker	Affiliation "Topic"
May	15	Prof. Hiroyuki Sakaki	The University of Tokyo “Progress in telecommunication technology and nanostructure devices”
June	18	Prof. Yoshihisa Yamamoto	Stanford University, USA “Hardware technology for quantum information processing”
July	10	Prof. Michael B. Santos	University of Oklahoma, USA “Novel electronic properties of narrow-gap quantum wells”
Aug.	28	Dr. Jeremy O'Brien	The University of New South Wales, Australia “STM fabrication of single phosphorus atom arrays for a silicon quantum computer & an investigation of the 0.7 feature in GaAs open quantum dots”
Aug.	30	Dr. Adrian Avramescu	The Institute of Physical and Chemical Research (RIKEN) “Growth of AlN-SiC solid solutions by sequential supply epitaxy”

Oct.	5	Dr. Huili Xing	University of California, Santa Barbara, USA “Progress in gallium nitride based bipolar transistors”
Oct.	9	Dr. Rudolf Hey	The Paul-Drude-Institute, Germany “Growth of a two-dimensional electron gas system of high mobility and density”
Oct.	11	Prof. Klaus H. Ploog	The Paul-Drude-Institute, Germany “Tunneling-induced spin injection from Fe and MnAs into GaAs”
Oct.	22	Prof. B. Monemar	Linkoping University, Sweden “Photoluminescence of excitons in $In_xGa_{1-x}N/In_yGa_{1-y}N$ multiple quantum wells”
Jan.	11	Prof. Yshai Avishai	Ben-Gurion University of the Negev, Israel “Electron tunneling through artificial and real molecules”
March	6	Prof. Harry W. Tom	University of California, Riverside, USA “Femtosecond laser-induced physical and chemical processes at surfaces”
March	7	Dr. J. Herfort	The Paul-Drude-Institute, Germany “Mound formation and its consequences for the growth of GaAs at low temperatures”

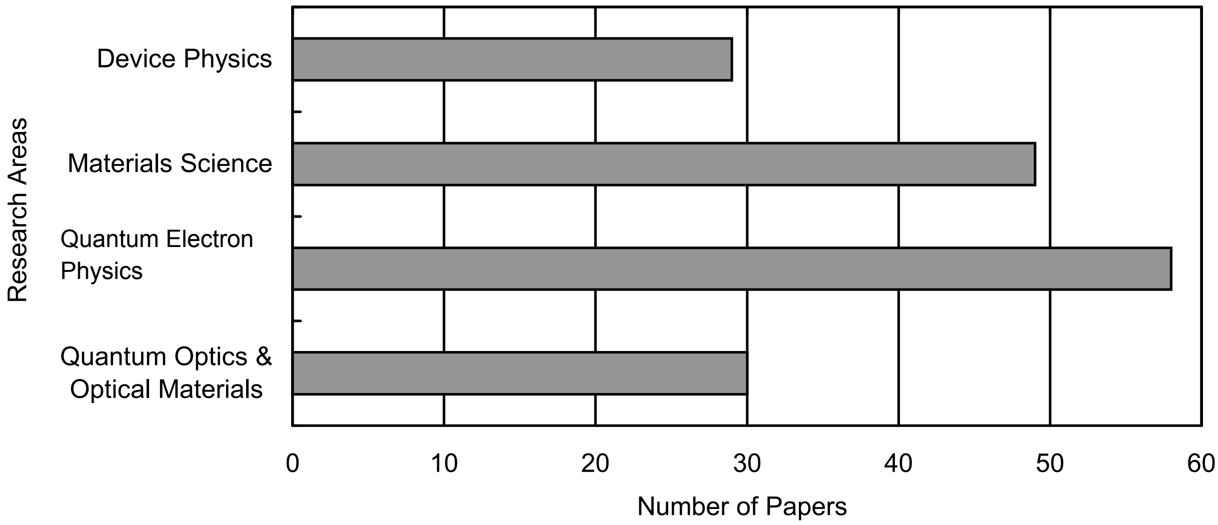
IV. Quantum Optics & Optical Materials

Date		Speaker	Affiliation "Topic"
April	5	Dr. Tetsuro Nikuni	The University of Toronto, Canada “Dynamics of Bose-Einstein condensed gases at finite temperature”
June	25	Prof. Kazumi Wada	Massachusetts Institute of Technology, USA “Si Micro-photonics”
Sept.	5	Dr. G. Ravindra Kumar	Tata Institute of Fundamental Research, India “Femtosecond, intense laser interaction with solids - hot electrons and megagauss magnetic fields”
Oct.	9	Prof. Wolfgang Husinsky	Vienna University of Technology, Austria “The possible role of ballistic electrons in ultra-fast laser ablation of metals: studied by pump-probe experiments”
Oct.	12	Prof. A. A. Andreev	Research Institute for Laser Physics, Russia “Generation of superstrong laser fields and their applications”

Jan.	22	Dr. Takashi Fujii	Central Research Institute of Electric Power Industry "Intense laser light propagation in the air using mobile TW-laser system"
Jan.	23	Dr. Takeya Tsurumi	The University of Tokyo "A Bose-Einstein condensate trapped in a torus potential"
Jan.	30	Dr. Paulo V. Santos	The Paul-Drude-Institute, Germany "Dynamical modulation of quantum wells by high-frequency fields"

Research Papers Published in International Journals (Fiscal 2001)

The number of research papers published in the international journals (English) in fiscal 2001 amounted to 166 in Basic Research Laboratories as a whole. The number of papers according to their research area is as follows.



The major journals and the number of published papers are shown below.

Specialized Journals

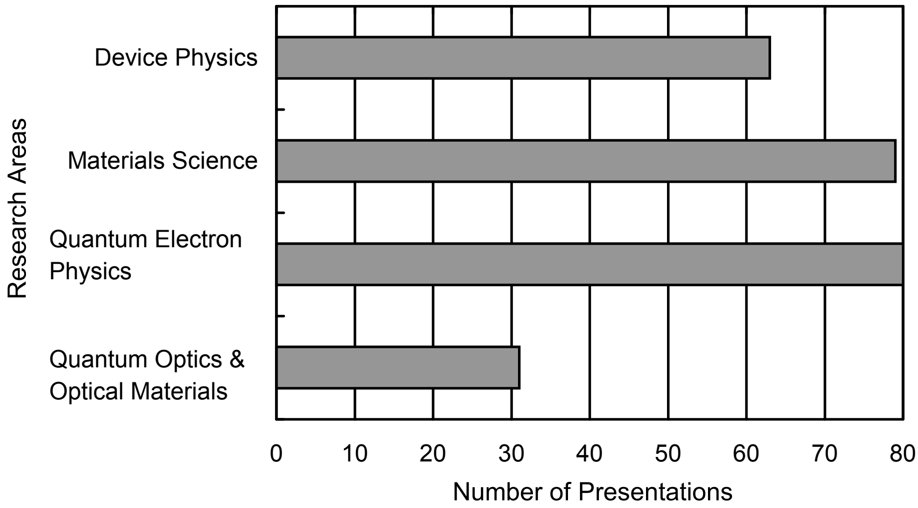
Name	(IF2000)*	Number
Applied Physics Letters	(3.906)	24
Physical Review B	(3.065)	12
Macromolecules	(3.697)	10
Japanese Journal of Applied Physics	(1.157)	10
Physical Review Letters	(6.462)	9
Surface Science	(2.198)	5
Journal of Applied Physics	(2.180)	5
Journal of Crystal Growth	(1.375)	5
Journal of Vacuum Science & Technology B	(1.605)	4
Material Science & Engineering B	(0.592)	4
Journal of American Chemical Society	(6.025)	3
Physical Review A	(2.831)	2
Journal of Physical Society of Japan	(1.943)	2
Reports on Progress in Physics	(9.000)	1
Advanced Materials	(5.522)	1
Chemical Communication	(3.695)	1
Optics Letters	(2.989)	1
Neuroscience Letters	(2.091)	1

* IF2000: Impact factor 2000 Journal Citation Reports, 2000)

The average impact factor for individual research papers from all NTT Basic Research Laboratories is 2.37

Presentations at International Conferences (Fiscal 2001)

The number of the presentations at the international conferences in fiscal 2001 amounted to 253 in Basic Research Laboratories as a whole. The number of presentations according to their research areas is as follows.



The major international conferences and the number of presentations are shown below.

Name	Number
14th International Conference on the Electronic Properties of Two-Dimensional System	16
13th International Conference on Crystal Growth/11th International Conference on Vapor-Phase Epitaxy	13
Mesoscopic Superconductivity and Spintronics	11
2001 International Conference on Solid State Devices and Materials	10
28th International Symposium on Compound Semiconductors	9
2001 Materials Research Society Fall Meeting	7
4th International Conference on Nitride Semiconductors	6
14th Pacific Rim Conference on Lasers and Electro-Optics	6
10th Narrow Gap Semiconductor Structures	5
American Physical Society March Meeting	4
International Symposium on Superconducting Device Physics 2001	4
8th International Conference on Formation of Semiconductor Interface	4
14th Annual Meeting of IEEE Lasers and Electro-Optics Society	3
4th International Symposium on Blue Laser and Light Emitting Diodes	3
43rd Electric Material Conference	3
International Workshop of Photonic and Electromagnetic Crystal Structures	3

List of Invited Talks at International Conferences (Fiscal 2001)

I. Device Physics

(1) Y. Takahashi, "Silicon single-electron devices and their circuit applications", The 1st Annual US-Korea-Japan Workshop on Nanostructure Science/Technology, Seoul, Korea (April, 2001).

(2) H. Kageshima, K. Shiraishi, and M. Uematsu, "Theory of Si oxide growth rate taking account of interfacial Si emission", Electrochemical Society International Semiconductor Technology Conference 2001, Shanghai, China (May, 2001).

(3) Y. Ono, K. Yamazaki, and Y. Takahashi, "Arithmetic operation by single-electron transistors", 2001 Silicon Nanoelectronics Workshop, Kyoto, Japan (June, 2001).

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